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2. EVIDENCE FOR TWO DIFFERENT SOLID PHASES OF TWO-DIMENSIONAL ELECTRONS IN HIGH MAGNETIC FIELDS
3. MICROWAVE SPECTROSCOPY OF THE BUBBLE PHASE IN 1/4 AND 3/4 FILLED HIGH LANDAU LEVELS
4. EVIDENCE OF A FIRST ORDER PHASE TRANSITION BETWEEN WIGNER CRYSTAL AND BUBBLE PHASES OF 2D ELECTRONS IN HIGHER LANDAU LEVELS

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**MICROWAVE SPECTROSCOPY OF STRONGLY CORRELATED 2D
ELECTRONS**

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INTRODUCTION

We have investigated the microwave absorption of clean two-dimensional (2D) electron systems (with mobility exceeding $10^7 \text{ cm}^2/\text{Vs}$) in GaAs/Al_xGa_{1-x}As heterostructures in high magnetic fields when the single particle energy spectrum is a series of discrete Landau levels. Our results, as summarized below, give direct evidence for the existence of several new phases of 2D electron matter and provide us new insights into the strong correlation physics therein.

WORK ACCOPMLISHED

1. Wigner crystal around integer Landau fillings

It is well known that at small landau level filling $\nu \lesssim 1/5$, following the termination of the fractional quantum hall effect (FQHE) series in the lowest Landau level, the ground state of a sufficiently clean 2D electron system is a Wigner crystal. Disorder pins the crystal to the semiconductor host lattice, rendering it an insulator. We discovered that in such high quality 2D electron systems, in the integer quantum hall effect regime, the electron (or hole) excitations in their sufficiently dilute limit also form Wigner crystals.

The discovery was made in an experiment where we observed a resonance in the real part of the finite frequency diagonal conductivity using microwave absorption measurements near integer fillings. The resonance exists in some neighborhood of filling factor around corresponding integers and is qualitatively similar to previously observed resonance of weakly pinned Wigner crystal in high B and very small filling factor regime. Data measured around $\nu=1, 2$ and 3 show clear signature of the Wigner crystal state around integer Landau levels.

2. Evidence for Two Different Solid Phases of Two-Dimensional Electrons in High Magnetic Fields

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We observed *two* different rf resonances in the frequency dependent real diagonal conductivity of very high quality two-dimensional electron systems in the high magnetic field insulating phase and interpret them as coming from *two* different pinned electron solid phases (labeled as “A” and “B”). The “A” resonance is observable for Landau level filling $\nu < 2/9$ [*reentrant* around the $\nu = 1/5$ fractional quantum Hall effect (FQHE)] and then *crosses over* to the different “B” resonance which dominates at sufficiently low ν . Moreover, the “A” resonance is found to show dispersion with respect to the size of the transmission line, indicating that the “A” phase has a large correlational length. We suggest that quantum correlations such as those responsible for FQHE may play an important role in giving rise to such different solids.

3. Microwave spectroscopy of the bubble phase in $\frac{1}{4}$ and $\frac{3}{4}$ filled high Landau levels

The FQHE is observed in the lowest four Landau levels with orbital Landau quantum number $N=0$ and 1. In higher Landau levels with $N \geq 2$, the Laughlin states are not favored and the 2D system is predicted to take on its Hartree-Fock ground states of stripes and bubbles.

Experimentally, early dc transport measurements showed a number of anomalous features. The most striking are the anisotropic diagonal resistance at half integer filling factors and the minima appearing at partial fillings $\nu^* \sim \frac{1}{4}$ and $\frac{3}{4}$, where $\nu^* = \nu - [\nu]$, $\nu > 4$, and $[\nu]$ is the greatest integer less than ν . Concomitantly, the Hall resistance in the latter case is quantized to the value of the adjacent integer quantum Hall effect plateau. This reentrant integer quantum Hall effect (RIQHE) was attributed to the bubble phase, which is a triangular crystal lattice with two or more electron guiding centers per lattice site.

We have applied microwave spectroscopy to study the RIQHE and measured the diagonal conductivity, σ_{xx} , in the microwave regime of an ultrahigh mobility two-dimensional electron system. We find sharp resonance in $\text{Re}[\sigma_{xx}]$ versus frequency when $\nu > 4$ and the partial filling of the highest Landau level, ν^* , is $\sim \frac{1}{4}$ or $\frac{3}{4}$ and temperatures $< 0.1\text{K}$. The resonance appears for a range of ν^* from 0.20 to 0.38 and again from 0.64 to 0.80. The peak frequency f_{pk} changes from ~ 500 to $\sim 150\text{MHz}$ as $\nu^* = \frac{1}{2}$ is approached. This range of f_{pk} shows no dependence on ν where the resonance is observed. The quality factor, Q , of the resonance is maximum at about $\nu^* = 0.25$ and 0.74. The experiment has yielded for the first time, spectroscopic information on the nature and the microscopic origin of the RIQHE.

4. Evidence of a first order phase transition between Wigner crystal and Bubble phases of 2D electrons in higher Landau levels

We have, for filling factors ν in the range between 4.16 and 4.28, simultaneously detected *two* resonances in the real diagonal microwave conductivity σ_{xx} of a two-dimensional electron system (2DES) at low temperature $T \approx 35\text{mK}$. We attributed the resonances to Wigner crystal and Bubble phases of the 2DES in higher Landau Levels. For ν below and above this range, only single resonances are observed. The coexistence of both phases is direct evidence of a first order phase transition. We estimate the transition point to be $\nu = 4.22$.

JOURNAL PUBLICATIONS

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- 5) "Evidence for two different solid phases of 2D electrons in high magnetic fields," Yong P. Chen, RM Lewis, LW Engel, DC Tsui, PD Ye, ZH Wang, LN Pfeiffer, and KW West. **Phys. Rev Lett.** 93 206805 (2004).